

# Simulation of $Z$ -boson $p_T$ spectrum at LHC and Tevatron using GR@PPA

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## Abstract

Predictions from the GR@PPA event generator concerning the transverse-momentum ( $p_T$ ) spectrum of  $Z$  bosons are compared with recent measurements at LHC and Tevatron. The simulation results are in reasonable agreement with the measurements, although marginal discrepancies are observed in high- $p_T$  regions. The principal agreements imply that the leading-order simulation with a primitive parton shower based on the leading-logarithmic approximation still provides a reasonable description of the transverse motion of the hard-interaction system in hadron collisions, without the need to introduce noble techniques to incorporate higher-order corrections.

## 1 Introduction

Hard interactions in hadron collisions, such as heavy particle productions, are associated with initial-state hadronic activities which induce a transverse motion of the hard-interaction system. Since the transverse motion affects the detection capability of experiments, a precise understanding of the activities is necessary not only for accurate measurements of known processes but also for obtaining insights into new physics, particularly for discovering the production of new heavy particles which may decay to final states including invisible particles. The measurement of  $Z$ -boson production provides a unique opportunity for studying these initial-state hadronic activities because the production kinematics can be unambiguously measured if the production is tagged by a pair of electrons or muons from its decay.

The dominant part of the hadronic activities that may affect the transverse motion of the hard interaction system is considered to be caused by higher-order strong-interaction (QCD) effects which can be evaluated perturbatively. The higher-order effects are dominated by those terms divergent at the limit where partons (light quarks and gluons) are radiated collinear to the incident beam directions. These divergent terms can be factorized and can be added to all orders of the QCD coupling,  $\alpha_s$ , to produce finite corrections. Thus, they are expected to be independent of the details of hard interactions. The  $Q^2$  evolution in parton distribution functions (PDF) is an implementation of this all-order summation for the longitudinal components.

The parton shower (PS) is a Monte Carlo (MC) implementation of the all-order summation. PS simulates transverse activities, which are ignored in PDFs, as well as the longitudinal evolution. Hence, MC event generators implementing PS are indispensable tools for evaluating the detection efficiency and acceptance of experiments at hadron collisions. The theoretical basis is identical for PS and the evolution in PDF. Although the theory is not ambiguous, the actual implementation of PS includes substantial ambiguities because the introduction of a model is necessary for determining the parton-branch kinematics. A certain model is also necessary for simulating non-perturbative effects. Therefore, there may be a substantial variation in the predictions from different event generators. Furthermore, for technical reasons, the approximation to the higher-order QCD effects is limited to the leading-logarithmic (LL) order in PS available at present. Higher-energy or higher-precision measurements may reveal the applicable limit of the approximation. Hence, we need to repeat studies to examine the reliability of event generators and PS every time when new data become available from experiments.

GR@PPA 2.8 [1, 2] is a program package including leading-order (LO) event generators for single and double weak-boson production in hadron collisions. Although all matrix elements (ME) are evaluated at LO, the event generators can reproduce weak-boson production kinematics in the entire phase space by combining non-radiative and radiative processes with a jet-matching method. The package includes PS programs in order to ensure sufficient performance of the matching method. The included PS simulates the higher-order QCD effects down to  $Q^2 = (5 \text{ GeV})^2$ . Further small- $Q^2$  phenomena, including non-perturbative effects, can be simulated by feeding the generated events to PYTHIA [3]. The PS in GR@PPA preserves primitive features of the LL approximation. It does not implement any noble techniques to import corrections from higher-order approximations, such as the angular ordering. The kinematics model is also very primitive [4, 5]. It strictly follows fundamental predictions from the massless approximation. Therefore, the comparison using this PS should provide a good test bench for probing the capability of the LL approximation.

We have shown in a previous study [5] that the GR@PPA event generator reproduces the transverse momentum ( $p_T$ ) spectrum of  $Z$  bosons produced at FNAL Tevatron, proton-antiproton ( $p\bar{p}$ ) collisions at the center-of-mass energy ( $\sqrt{s}$ ) of 1.8 and 1.96 TeV, with good precision. Recently, the ATLAS experiment has published their measurement result [6] at CERN LHC, proton-proton ( $pp$ ) collisions at  $\sqrt{s} = 7 \text{ TeV}$ . In this article, we examine the performance of the GR@PPA event generator and its PS by comparing the simulation results with the ATLAS measurement. Comparisons are also made with the latest  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$  results from the D0 experiment at Tevatron. Although the  $Z \rightarrow e^+e^-$  result from D0 has already been used in the previous study, the study is extended to more details in this article. The simulations are carried out by using the GR@PPA 2.8.3 update release [2] through the present study.

The GR@PPA event generator uses a forward-evolution PS (QCDPS) for simulating the initial-state QCD activities as the default. All PS programs in GR@PPA are based on the LO splitting functions with  $\alpha_s$  at the 1-loop approximation. Therefore, in the default setting, we can use only those PDFs which are based on the same approximation. Otherwise, the QCD evolution of QCDPS leads us to parton distributions which are different from those in the selected PDF at large  $Q^2$  relevant to the interested hard interactions. However, it is known that the LO QCD evolution necessarily gives a substantial deficit of quark densities in medium  $x$  ( $\sim 0.01 - 0.1$ ) regions relevant to weak-boson productions at high-energy hadron colliders [7]. It is suggested that it would be better to use next-to-leading order (NLO) PDFs even with LO event generators to obtain reasonable predictions. However, NLO PDFs give a small gluon density at small  $x$  ( $\lesssim 10^{-3}$ ). This is not suitable for LO event generations for charm and bottom quark productions, and the underlying-event simulation [7].

The so-called modified leading-order (LO\*) PDFs have been proposed to overcome these difficulties [7, 8]. Maintaining a high density of gluons at small  $x$ , they significantly enhance the quark densities in medium- $x$  regions by relaxing the momentum sum rule at small  $Q^2$  where the evolution originates. In addition, it is also known that the 1-loop  $\alpha_s$  approximation is not sufficient for reproducing the evolution at small- $Q^2$  regions. The application of the 2-loop  $\alpha_s$  gives us apparently better fits to small- $Q^2$  DIS data from HERA experiments even with LO PDFs. For this reason, many of the recent PDFs are using the 2-loop  $\alpha_s$  even if the evolution is at the leading order.

In the present study, we use LO\* and NLO PDFs with the GR@PPA event generator. Although the  $Q^2$  evolution is performed based on the LO approximation in LO\* PDFs, the evolution in NLO PDFs is explicitly different from that in GR@PPA. A backward-evolution PS (QCDPSb) is provided in GR@PPA for adopting such PDFs based on different assumptions. In order to make the basic setup common to all simulations, we use QCDPSb for the initial-state PS through the study. Most of the applied PDFs employ the 2-loop  $\alpha_s$  for the evolution. Therefore, there may be a mismatch also in the  $\alpha_s$  approximation. We have improved the definition of  $\Lambda_{\text{QCD}}$  in QCDPSb in order to perform a consistent evolution in such cases [2].

The remainder of this article is organized as follows. The simulation results are compared with the measurement by ATLAS in Sec. 2. The simulations with NLO PDFs are discussed along with those using LO\* and LO PDFs. Comparison with the D0 data is carried out in Sec. 3, and the discussions are concluded in Sec. 4.

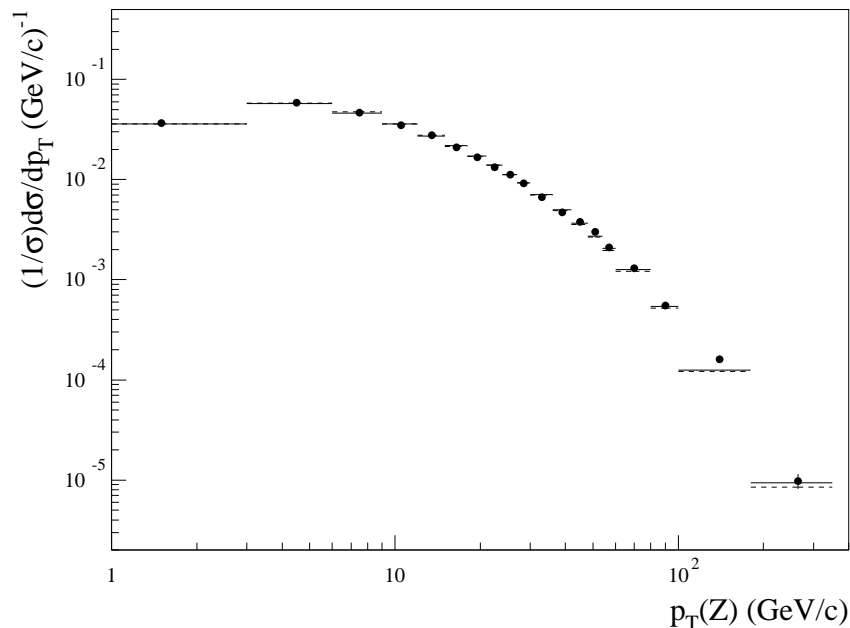


Figure 1: Normalized  $p_T$  distribution of  $Z$  bosons in the 7-TeV LHC condition. The measurement result from ATLAS (filled circles) is compared with the GR@PPA simulations using MRST2007lomod (solid bars) and CT09MC1 (dashed bars) for PDF.

## 2 Comparison with the ATLAS measurement

Since the main use of MC event generators is for the evaluation of the acceptance and efficiency of measurements, the relative shape of kinematical distributions is more important than the absolute value of the cross sections. Hence, we examine the  $p_T$  distribution normalized to the total cross section,  $(1/\sigma)d\sigma/dp_T$ , in the present study. Figure 1 compares the GR@PPA simulation results with the ATLAS measurement [6] in this quantity. Two simulation results are presented: one with the MRST2007lomod PDF [7] and the other with CT09MC1 [8]. The simulations were carried out for the 7-TeV LHC condition,  $pp$  collisions at  $\sqrt{s} = 7$  TeV, by setting the renormalization scale ( $\mu_R$ ) and factorization scale ( $\mu_F$ ) equal to the  $Z$ -boson mass,  $m_Z = 91.19$  GeV/ $c^2$ . The energy scale for the final-state PS was also set to the same value. The PDFs were referred to by using the LHAPDF library [9].

The events were generated with a constraint on the  $Z$ -boson invariant mass of  $66 \leq m_Z \leq 116$  GeV/ $c^2$ . The parton showers were applied down to  $Q^2 = (5 \text{ GeV})^2$  in GR@PPA. The backward-evolution PS (QCDPSb) was used for the initial state. As usual, the generated events were passed to PYTHIA for simulating lower- $Q^2$  phenomena down to the hadron level. The PYTHIA version 6.425 was used for this simulation. The default setting in PYTHIA was unchanged except for the setting of  $\text{PARP}(67) = 1.0$  and  $\text{PARP}(71) = 1.0$ , as in the previous study [5]. After applying the PYTHIA simulation, we constrained the pseudorapidity ( $\eta$ ) and transverse momentum ( $p_T$ ) of the decay leptons as  $|\eta| \leq 2.4$  and  $p_T \geq 20$  GeV, following the signal definition of ATLAS. These conditions were imposed on the quantities before adding the photon-radiation effects in the decay, according to the ATLAS definition.

We can see an overall agreement between the simulations and the measurement in Fig. 1. However, details are invisible because the results extend to a very wide range of approximately four orders of magnitude. In order to closely examine the details, we have plotted the ratio of the data to a simulation result in Fig. 2. Here, first of all, we used the simulation with MRST2007lomod as the

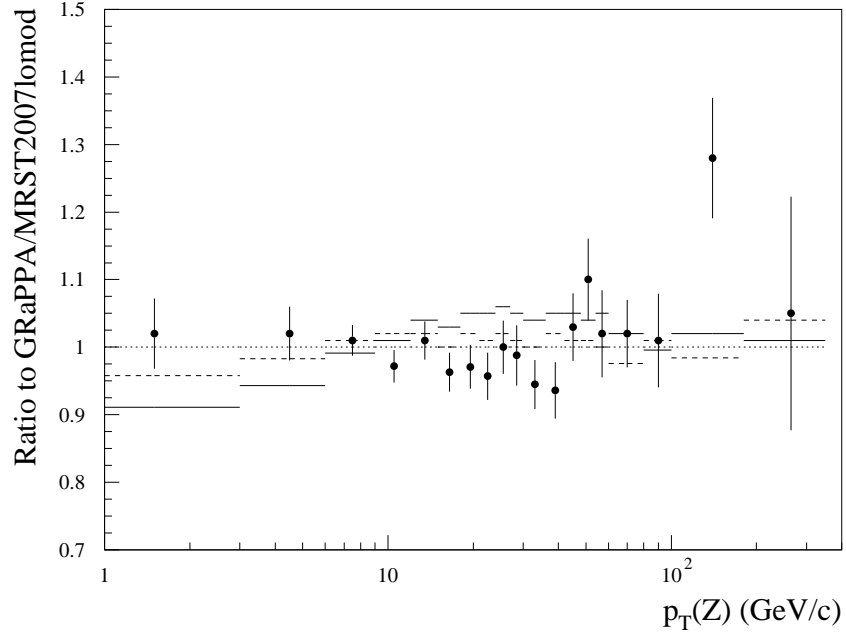


Figure 2: The ratio of the ATLAS data to the GR@PPA simulation with the MRST2007lomod PDF. The solid bars show a test simulation result in which the  $\Lambda_{\text{QCD}}$  value is increased to 0.165 GeV, and the dashed bars illustrate the result from the simulation with CTEQ6L1.

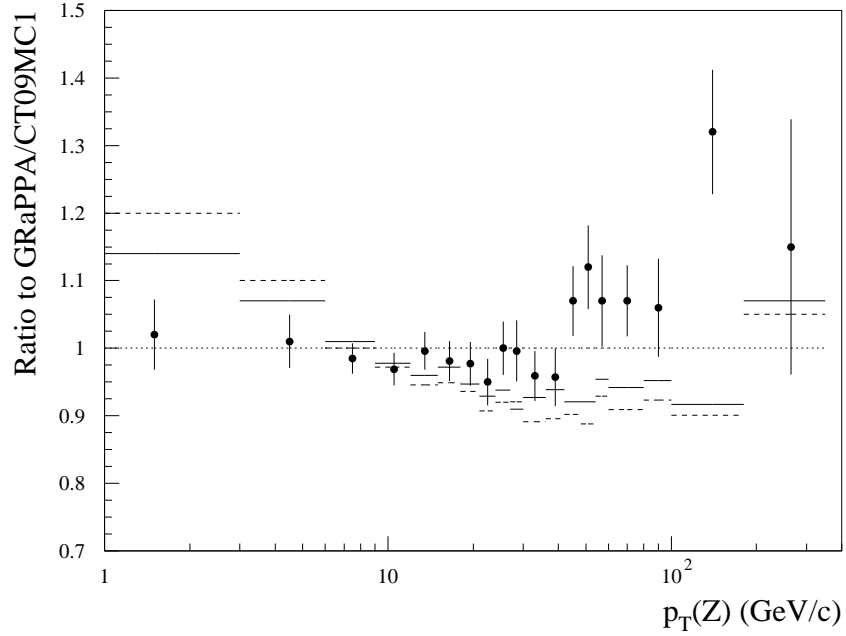


Figure 3: The ratio of the ATLAS data to the GR@PPA simulation with the CT09MC1 PDF. Solid and dashed bars show the simulation results with NLO PDFs, MSTW2008nlo and CT10, respectively.

reference, because the ATLAS group has stated that the PYTHIA simulation with this PDF shows good agreement with their measurement. We can observe good agreement between the simulation and the data within the quoted measurement uncertainty even with the GR@PPA simulation, throughout the measurement range except for the second-highest  $p_T$  bin.

MRST2007lomod is a so-called LO\* PDF and uses the 2-loop  $\alpha_s$  for the evolution with  $\Lambda_{\text{QCD}} = 0.241$  GeV. This  $\Lambda_{\text{QCD}}$  value corresponds to the  $\alpha_s(m_Z^2)$  value of 0.119. Therefore, this is a good test case for our definition of  $\Lambda_{\text{QCD}}$ . GR@PPA adjusts the  $\Lambda_{\text{QCD}}$  for PS so that the used 1-loop  $\alpha_s$  should reproduce the 2-loop  $\alpha_s$  in PDF as precisely as possible [2]. The adjustment gives a  $\Lambda_{\text{QCD}}$  value of 0.116 GeV, which leads to  $\alpha_s(m_Z^2) = 0.123$ . The result in Fig. 2 implies that this definition is reasonable.

As a test, we carried out a simulation with  $\Lambda_{\text{QCD}} = 0.165$  GeV, the default setting in the original GR@PPA 2.8. This value is adopted in CTEQ6L1 [10], an LO PDF employing the 1-loop  $\alpha_s$  leading to  $\alpha_s(m_Z^2) = 0.130$ . The ratio to the current default result is shown with solid bars in Fig. 2. We can see a significant discrepancy from the data with this choice. From this result, we can also find that the  $p_T$  range can be subdivided to three regions:  $p_T \lesssim 10$  GeV ( $R_1$ ),  $10 \lesssim p_T \lesssim 100$  GeV ( $R_2$ ), and  $p_T \gtrsim 100$  GeV ( $R_3$ ). In the previous study, we found that the primordial  $k_T$  simulation in PYTHIA determines the shape within  $R_1$ , whereas it does not alter the distribution in  $R_2$  and  $R_3$ . The results in Fig. 2 show that the balance between the fractions in  $R_1$  and  $R_2$  is a good measure for the validation of the PS simulation. The fraction in  $R_2$  increases as we choose larger  $\Lambda_{\text{QCD}}$  values leading to larger values of  $\alpha_s$ , and the fraction in  $R_1$  decreases to compensate for it. The fraction in  $R_3$  is nearly independent of these simulations because it is predominantly determined by the  $Z + 1$  jet cross section.

The dashed bars in Fig. 2 show the result from the simulation with the CTEQ6L1 PDF. Of course,  $\Lambda_{\text{QCD}} = 0.165$  GeV is assumed with the 1-loop  $\alpha_s$  in this simulation. Despite this assumption, although a slight enhancement is seen in the  $R_2$  region, the result does not show a large discrepancy from the MRST2007lomod result. The input parton distributions at small  $Q^2$  must be appropriately adjusted in CTEQ6L1 to give comparable distributions in the relevant  $Q^2$  range. Although the forward-evolution PS can be used with this PDF, the presented result has been obtained with the backward-evolution PS. We have confirmed that the application of the forward-evolution PS does not significantly alter the result.

Figure 3 shows the result in which the GR@PPA simulation with another LO\* PDF, CT09MC1, is used as the reference. Contrary to MRST2007lomod, CT09MC1 uses the 1-loop  $\alpha_s$  for the evolution; thus,  $\alpha_s(m_Z^2) = 0.130$  and the  $\alpha_s$  value is always larger than the MRST2007lomod value by about 10% in the GR@PPA PS. Despite such a difference, the result in Fig. 3 is nearly identical to the previous result in Fig. 2. This agreement further justifies our method for determining the  $\Lambda_{\text{QCD}}$  value. However, the high- $p_T$  behavior of this result is a little bit strange.

GR@PPA uses the  $\alpha_s$  value that is given by the selected PDF for the calculation of matrix elements. The high- $p_T$  ( $\gtrsim 100$  GeV/ $c$ ) cross section is determined by  $Z + 1$  jet matrix elements which are proportional to  $\alpha_s$ . Thus, as a naive speculation, the  $R_3$  fraction of the simulation with CT09MC1 should be larger than that of the simulation with MRST2007lomod by about 10%, since we always set  $\mu_R = m_Z$ . In other words, the ratio of the data shown in Fig. 3 should be smaller than that in Fig. 2 by about 10% in the region  $R_3$ . This amount of systematic difference should be visible because the statistical error of the simulation is only 3.6% in the highest  $p_T$  bin and 1.5% in the second highest bin in these simulations. However, no such tendency is observed. This is mainly because the  $q\bar{q} \rightarrow Z$  cross section of the simulation with CT09MC1 is significantly ( $\sim 9\%$ ) larger than the simulation with MRST2007lomod, owing to a larger enhancement of the quark density in CT09MC1.

The gluon density contributes to the  $Z + 1$  jet cross section through the  $qg \rightarrow Z + q$  interaction. Therefore, if there is no difference in the gluon density, the larger quark density should lead to another enhancement in the high- $p_T$  cross section of the simulation with CT09MC1, in addition to the enhancement due to the larger  $\alpha_s$  value. Thus, the high- $p_T$  cross section of the simulation with CT09MC1 should be larger than that of the simulation with MRST2007lomod by more than 10% from this naive estimation. However, the enhancement is only 5% near  $p_T = 100$  GeV/ $c$ . As a result, contrary to the naive expectation, the high- $p_T$  fraction of the former becomes about 4% smaller than the fraction of the latter. This implies that the difference in the gluon density must also be substantial.

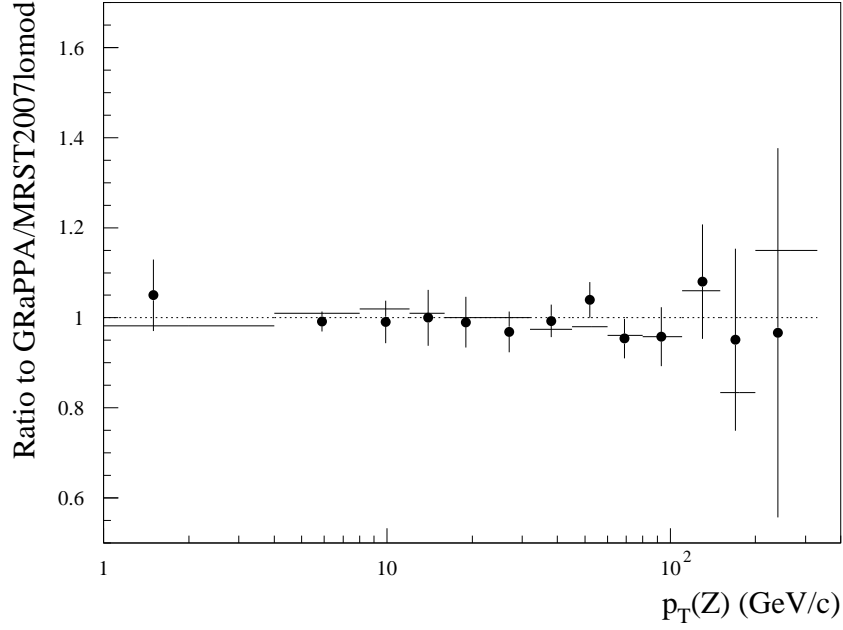


Figure 4: The ratio of the  $Z \rightarrow \mu^+\mu^-$  data from D0 to the GR@PPA simulation with MRST2007lomod. The solid bars show the simulation result with the CT09MC1 PDF. The D0 data are extrapolated to the condition of  $65 \leq m_Z \leq 115 \text{ GeV}/c^2$  with  $|\eta(\mu)| \leq 1.7$  using the correction factors presented in their report. The simulation results are obtained with the same condition. The muon properties without the photon radiation effect are used to define the condition.

As we have seen in the above, the studied LO\* and LO PDFs provide nearly identical  $Z$ -boson  $p_T$  spectra, despite there being substantial differences in the setting of the fundamental parameters and assumptions between them. The parton distributions in the PDFs must have been appropriately adjusted through the fits to experimental measurements. However, this fact does not imply that the  $Z$ -boson  $p_T$  spectrum is insensitive to the variation in PDF.

It is suggested for many years that it would be better to use NLO PDFs even with LO event generators to obtain reasonable predictions, particularly concerning rapidity distributions. We have tested such simulations employing recent NLO PDFs. The results are plotted in Fig. 3. The solid bars illustrate the result obtained with the MSTW2008nlo [11] PDF, and dashed bars with CT10 [12]. The two results show a nearly identical behavior and fail to reproduce the measurement data. The fraction in the  $R_1$  region is too large and, correspondingly, too small in  $R_2$ . We have observed similar results from the simulations with the PYTHIA built-in generator.

Similar results have also been obtained in the report from ATLAS [6] for NLO predictions in which NLO PDFs are employed. It should be reminded that the  $p_T$  spectrum is evaluated on the basis of the tree-level MEs for  $Z + 1$  jet processes even in NLO calculations. Among several NLO predictions, the RESBOS prediction provides a reasonable explanation of the measurement in the ATLAS report. This is because the compared RESBOS prediction is corrected by using a K-factor derived from a next-to-next-to-leading order (NNLO) calculation. These facts imply that there must be a fundamental mismatch between tree-level MEs and NLO PDFs.

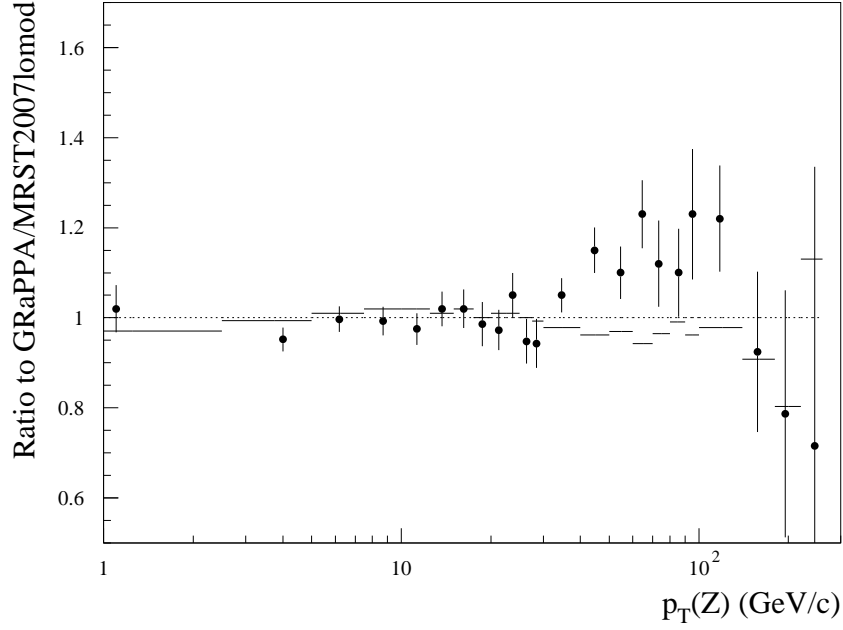


Figure 5: The ratio of the  $Z \rightarrow e^+e^-$  data from D0 to the GR@PPA simulation with MRST2007lomod. The solid bars show the result with the CT09MC1 PDF. The simulation results are obtained for the  $Z$ -boson mass constraint of  $40 \leq m_Z \leq 200 \text{ GeV}/c^2$  with no cut on the decay electrons, according to the definition by D0.

### 3 Comparison with the D0 measurements

In this section, we compare the GR@PPA simulation results with the  $Z$ -boson  $p_T$  spectrum data from the D0 experiment at Tevatron Run-II,  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$ . We first examine the measurement on the  $Z \rightarrow \mu^+\mu^-$  channel recently published [13]. D0 has presented a result for a constraint close to their actual detection condition. The condition that they have defined is not convenient for simulations because it is not easy to guarantee the accuracy of the simulation for the final-state photon radiation effect. Instead, we extrapolate the D0 data to the simplified detection condition,  $65 \leq m_Z \leq 115 \text{ GeV}/c^2$  with  $|\eta(\mu)| \leq 1.7$ , using the correction factors provided in their paper. We have multiplied their measurement data with those factors denoted by " $p_T^\mu$ " and "FSR" in Table 1 of the paper. Thus, we can consider that the constraints are satisfied in the properties without the final-state photon radiation effects. The simulations have been carried out with this assumption.

Figure 4 shows the ratio of the D0 data to the GR@PPA simulation with MRST2007lomod. The error bars were evaluated by the quadratic sum of all errors presented in the D0 paper. We can see that the agreement is very good throughout the measurement range. The solid bars in Fig. 4 show the simulation result with CT09MC1. The PDF dependence is very small compared to the measurement error.

Next, we examine the D0 data on the  $Z \rightarrow e^+e^-$  channel published several years ago [14]. The data presented in the report are extrapolated to those with a very loose constraint,  $40 \leq m_Z \leq 200 \text{ GeV}/c^2$  without any cut on electrons. Simulations were carried out for this condition. Figure 5 shows the ratio of the D0 data to the simulation with MRST2007lomod. The agreement is very good at low  $p_T$  ( $\lesssim 40 \text{ GeV}/c$ ) whereas a systematic enhancement of the data or deficit of the simulation is observed in the  $p_T$  range of  $40 \lesssim p_T \lesssim 140 \text{ GeV}/c$ . The solid bars in Fig. 5 show the simulation result with CT09MC1. The PDF dependence is small compared to the measurement error.

The discrepancy in the high  $p_T$  region described above was also observed by D0 in the comparison of

their result with NLO and resummation predictions [14]. A similar enhancement at high  $p_T$ , or a jump of the cross section around  $p_T = 40 \text{ GeV}/c$  ( $\sim m_Z/2$ ), is also seen in the ATLAS result in Figs. 2 and 3, although the significance is marginal. On the other hand, no such disagreement is observed in the D0  $Z \rightarrow \mu^+ \mu^-$  data shown in Fig. 4. It is impossible to reproduce these observations simultaneously with our simulation. Although these observations may suggest a defect in the simulation or a sign of new physics, we also suspect a common problem in the measurements. The  $p_T$  spectrum of decay leptons is broadened as the  $p_T$  of  $Z$  bosons ( $p_T(Z)$ ) increases. Accordingly, the inefficiency due to the  $p_T$  cut in the lepton detection becomes larger in higher  $p_T(Z)$  bins. An underestimation of the efficiency or a shift in the energy scale at small  $p_T$  near the detection threshold may result in a systematic enhancement of the cross section at high  $p_T(Z)$ . In any case, the observed discrepancies are still marginal compared to the measurement errors. Hence, more precise measurements with improved statistics at LHC are awaited in order to clarify the reasons for these observations.

## 4 Conclusions

$Z$ -boson production is a unique place for measuring the initial-state hadronic activities in hadron collisions, which are considered to be common to all hard interactions. The PS in GR@PPA, which simulates dominant parts of the hadronic activities, strictly preserves primitive features of the LL approximation of QCD. Hence, the comparison of its prediction with measurement data provides us with a unique opportunity for probing the applicable limit of the LL approximation.

In this article, we have compared the predictions from the GR@PPA event generator with recent measurements on the  $Z$ -boson  $p_T$  spectrum at LHC and Tevatron. We have primarily used recently-proposed LO\* PDFs for the simulation, in combination with a backward-evolution PS. The predictions with the MRST2007lomod and CT09MC1 PDFs have been discussed. Although the approximation order of  $\alpha_s$  is different between the two PDFs, an appropriate definition of the strong-interaction coupling  $\alpha_s$  in GR@PPA has made it possible to carry out a consistent simulation.

The simulation results are in good agreement with the measurement data, at least in low- $p_T$  regions,  $p_T \lesssim 40 \text{ GeV}/c$ , where accurate data are available and the multiple radiation by PS predominantly determines the spectrum. The agreement is well within 5%. The difference between the predictions with the two PDFs is smaller than this level. We have also found that the difference to the prediction with the LO PDF is not remarkable in the  $p_T$  spectrum. On the other hand, simulations with NLO PDFs show significant discrepancies from the measurements. There must be a fundamental mismatch in the combination of tree-level matrix elements with NLO PDFs.

Although the overall shape is consistent, the  $Z \rightarrow e^+ e^-$  data from D0 at Tevatron show a substantial enhancement of more than 10% with respect to the simulations in the  $p_T$  range of  $40 \lesssim p_T \lesssim 140 \text{ GeV}/c$ . A similar enhancement is also seen in the ATLAS data, whereas no such enhancement is observed in the  $Z \rightarrow \mu^+ \mu^-$  data from D0. The observed discrepancies are still marginal and precise measurements with improved statistics at LHC are awaited for further discussions.

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## References

- [1] S. Odaka and Y. Kurihara, *GR@PPA 2.8: initial-state jet matching for weak-boson production processes at hadron collisions*, Comput. Phys. Commun. **183** (2012) 1014; arXiv:1107.4467.
- [2] S. Odaka, *GR@PPA 2.8.3 update*, arXiv:1201.5702.
- [3] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP **05** (2006) 026; arXiv:hep-ph/0603175.
- [4] S. Odaka, Y. Kurihara, *Initial-state parton shower kinematics for NLO event generators*, Eur. Phys. J. C **51** (2007) 867; arXiv:hep-ph/0702138.
- [5] S. Odaka, *Simulation of Z boson  $p_T$  spectrum at Tevatron by leading-order event generators*, Mod. Phys. Lett. A **25** (2010) 3047; arXiv:0907.5056.
- [6] ATLAS Collaboration, G. Aad *et al.*, *Measurement of the transverse momentum distribution of  $Z/\gamma^*$  bosons in proton-proton collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, Phys. Lett. B **705** (2011) 415; arXiv:1107.2381.
- [7] A. Sherstnev and R. S. Thorne, *Parton Distributions for LO Generators*, Eur. Phys. J. C **55** (2008) 553; arXiv:0711.2473.
- [8] H.-L. Lai *et al.*, *Parton Distributions for Event Generators*, JHEP **04** (2010) 035; arXiv:0910.4183.
- [9] M. R. Whalley, D. Bourilkov, and R. C. Group, *The Les Houches Accord PDFs (LHAPDF) and Lhaglu*, arXiv:hep-ph/0508110.
- [10] J. Pumplin *et al.*, *New generation of parton distributions with uncertainties from global QCD analysis*, JHEP **07** (2002) 012; arXiv:hep-ph/0201195.
- [11] A. Martin, W. Stirling, R. Thorne, and G. Watt, *Parton distributions for the LHC*, Eur. Phys. J. C **63** (2009) 189; arXiv:0901.0002.
- [12] H.-L. Lai *et al.*, *New parton distributions for collider physics*, Phys. Rev. D **82** (2010) 074024; arXiv:1007.2241.
- [13] D0 Collaboration, V. M. Abazov *et al.*, *Measurement of the normalized  $Z/\gamma^* \rightarrow \mu^+\mu^-$  transverse momentum distribution in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV*, Phys. Lett. B **693** (2010) 522; arXiv:1006.0618.
- [14] D0 Collaboration, V. M. Abazov *et al.*, *Measurement of the shape of the boson transverse momentum distribution in  $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^- + X$  events produced at  $\sqrt{s} = 1.96$  TeV*, Phys. Rev. Lett. **100** (2008) 102002; arXiv:0712.0803.